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Impact of Road Pavement Condition on Vehicle Free Flow Speed, Vibration, and In-vehicle Noise

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Abstract

Road infrastructure in good condition is a key requirement for efficient transportation systems which leads to economic prosperity and improved quality of life. However, road surface conditions deteriorate over time according to traffic loads and environmental factors. Poor road conditions lead to congestion, accidents, lost productivity, and driver fatigue. This work considers the relationship between road pavement condition and vehicle speed, vibration, and in-vehicle noise. A 7 km section of the Grand Trunk Road, Peshawar, Pakistan divided into 280 segments (140 for each lane), of length 50 m was observed and the Pavement Condition Index (PCI) of each segment was determined based on the recurrent distress type and density according to ASTM D6433-011 guidelines. The number of very good, satisfactory, fair, poor, and very poor conditions are 51, 52, 81, 48, and 42, respectively. The mobile app BotlnckDectr was employed to measure vehicle speed, RPM, noise, vibration, GPS location, and time. Statistical analysis was employed to determine the relationship between PCI and vehicle speed, vibration, and in-vehicle noise. The results obtained indicate that noise and vibration increase by 3.3% and more than 30%, respectively, as the pavement condition changes from good to very poor, and vehicle speed decreases by 8.8%.

Keywords: *Pavement Condition Index (PCI), pavement distress, road pavement condition, in-vehicle noise, vibration, vehicle speed*

1. Introduction

Reliable transportation infrastructure is important for safe and efficient traffic flows. This requires a road network with good pavement (road surface) conditions. However, pavement conditions degrade over time due to traffic overloading, environmental factors, and road construction deficiencies [1,2]. Pavement condition affects travel cost and time. It has been reported that travel costs can be reduced from US $1.84/vehicle-km to US $0.055/vehicle-km [3] with road improvements. Travel cost has been shown to decrease from US $4.44/vehicle to US $1.66/vehicle when old pavement is replaced with new pavement [3]. Pavement condition contributes to accident and injury rates. Poor pavement with low skid resistance has a severe crash mean of 1.65 while poor and very good pavement have means of 1.59 and 1.54, respectively [4]. Thus, road networks should be maintained at an acceptable level through regular rehabilitation, maintenance, and construction.

Research Context - It is imperative to identify pavement distress and its impact on vehicles and drivers. The safety and comfort of road users decrease as the pavement deteriorates. Pavement distress can be categorized into three types: linear measured distress (such as longitudinal wheel path cracks, joint cracks, and meandering cracks), area measured distress (such as alligator cracks), and numbered measured distress (such as transverse cracks and potholes) [5]. Pavement surface conditions can negatively affect vehicle speed, vibration, and in-vehicle noise. These effects are a major cause of traffic accidents, congestion, and overall increased travel times. Moreover, vehicle vibration and in-vehicle noise

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result in driver and passenger physiological and psychological discomfort. Therefore, it is important to understand the relationships between pavement condition and vehicle speed, vibration, and in-vehicle noise.

Scope and Objectives - The field study reported in this paper is divided into two phases. In the first phase, the Pavement Condition Index (PCI) was determined for the Grand Trunk Road, Peshawar, Pakistan, which is a 7 km two-lane main arterial highway. For this purpose, the highway was divided into 50 m segments for a total of 240 segments. Manual inspection was employed to assess road pavement distress (type, severity, and quantity), in each segment and then a PCI was assigned. In the second phase, a test vehicle was driven over each lane 16 times from 12 AM to 2 AM. An OBD-II scanner connected to the BotlnckDectr mobile app was used to record parameters such as vehicle speed, RPM, in-vehicle noise, vibration, GPS location, and time [6]. These parameters were sent to the Amazon Web Services (AWS) cloud platform using a smartphone. The data were analyzed to achieve the following objectives.

1. Determine the variations in vehicle speed, vibration, and in-vehicle noise with respect to the PCI of each segment.
2. Establish the correlation between PCI and in-vehicle noise level for different vehicle speeds.

The rest of this paper is arranged as follows. Section II presents the related work. The methodology is given in Section III and the performance is evaluated in Section IV. Finally, some conclusions are presented in Section V.

2. Related work

A road network with good pavement conditions is essential to the economic prosperity of a country. Thus, timely road pavement assessment and maintenance are essential. In a study [5], the PCI was proposed for road pavement assessment. It employs a rating scale where 100 denotes ideal road pavement condition while 0 denotes failed condition as shown in Figure 1. The PCI has since become a well-established and widely accepted numerical indicator of pavement condition.

In a study [7], road pavement condition was assessed on a highway in Koums City, Libya, via manual inspection. The methodology employed was based on the guidelines in ASTM standard D-6433-07. The road distress and severity level were used to assign a PCI value to each 50 m road segment. It was concluded that the road distress was primarily longitudinal and transversal cracks.

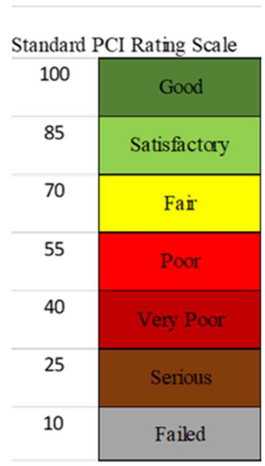

Figure 1. The Pavement Condition Index (PCI) and rating scale with the corresponding colors [5].

In a study [8], driver behavior was examined for motorcycles and light and heavy vehicles on poor condition pavement in 8 road sections in Bandung City, Indonesia. It was observed that motorcycles tend to change lanes to avoid poor condition pavement while heavy vehicles tend to reduce their speed.

2.1. Pavement condition and vehicle noise

In a study [9], vehicle noise due to pavement-tire interaction on eight asphalt and four concrete road sections. The test vehicles employed were two-wheelers, auto-rickshaws, and light and heavy commercial vehicles. These vehicles were driven at different speeds and the noise levels recorded using an SVAN 946A sound meter. The influence of vehicle type/speed/load, pavement type/temperature, and wind direction on the noise level was analyzed to obtain regression models for tire-pavement interaction noise levels. It was concluded that speed was the most significant parameter for noise generation. For example, the noise level increase from 5 dB to 6 dB for heavy commercial vehicles with an increase in speed from 30 km/h to 50 km/h. This increase can be attributed to tread impact and adhesion. Furthermore, it was reported that the noise level is generally 2 dB higher on concrete pavement for the same vehicle and tire types compared to asphalt pavements.

In a study [10], the impact of pavement type on in-vehicle noise was examined for a 9 mi section of the US-59 freeway in Houston, TX, USA. Part of this section had concrete pavement while the remainder had newly laid asphalt pavement. One year and four-year-old door sedans were driven for 20 to 30 min. Data was recorded using an onboard diagnostic system including a sound meter, GPS, and smartphone app. It was reported that in-vehicle noise was approximately 6 dB lower on asphalt pavement at 95.6 km/h.

In a study [11], noise levels were measured using the Close ProXimity (CPX) method on six different road sections. The test vehicle had a laser profiler mounted in the front and a semi-anechoic chamber with a reference tire (Pirelli P6000) located in the rear. Pavement-tire interaction noise levels were measured using two microphones. The noise levels were measured on the same road sections in 2013 and 2015 at a speed of 50 km/h. It was concluded that the noise levels were higher in 2015 due to road pavement deterioration. In a study [12], pavement-tire interaction noise levels were measured on 21 road sections using the CPX method. These sections had varying distress levels for Graded Asphalt Rubber (GGAR), Asphalt Concrete (AC), and Gap Graded Asphalt (GGA) pavement. The noise levels were recorded on each road section using two type 4190 microphones at 30, 50, and 65 km/h. It was observed that the noise level increases as the pavement condition decreases. Furthermore, AC and GGAR pavement with alligator cracks produced the higher noise levels.

2.2. Pavement condition and vehicle vibration

Vehicle vibration is a major issue because of the passenger discomfort and physiological damage it causes. In a study [13], a road section with a series of bumps was investigated. The test vehicle had tri-axial accelerometers mounted under the front and rear seats. The road vibration was 0.54 g at 40 km/h, 0.60 g at 60 km/h, and 0.64 g at 80 km/h. Thus, the vibration exceeded the maximum safe value of 0.60 g recommended in ISO 2631 at 60 and 80 km/h. In a study [14], vehicle vibration was recorded on a road section before and after flexible pavement was laid. Two accelerometers (4508B1, 10 mV/g, 0.1 Hz to 8 kHz and 4508B, 100 mV/g, 0.3 Hz to 8 kHz), were mounted on the front wheel and chassis of a 2002 OPEL Vectra B1.8 with standard tires. The test vehicle was driven at 40, 50, and 80 km/h. It was concluded that there was a significant difference in vehicle vibration before and after the pavement was changed.

In a study [15], a smartphone app was developed to estimate the International Roughness Index (IRI) of road surfaces. Tests were carried out on 20 segments of a 179 km road. The IRI was estimated using a laser profiler (Hawkeye 2000) and two smartphone apps (Anrosensor and Roadroid). The estimated IRI using the proposed app had 75.4% similarity with the laser profiler, but Roadroid provided better results. In a study [16], a smartphone app was developed for pothole/bump identification using the accelerometer and GPS. The results obtained indicate this app can be used to estimate pavement condition.

2.3. Pavement condition and vehicle speed

In addition to noise and vibration, the pavement condition has an impact on vehicle speed. A decrease in PCI will result in a lower speed. In a study [17], vehicle speed was examined on both distressed and non-distressed road sections. The road pavement condition was determined via visual observations and traffic data were collected at selected sites. The 50th and 85th speed percentiles were calculated for each type of vehicle. The results obtained show that the speed is higher on non-distressed road surfaces regardless of the type of vehicle. However, the effect of speed on PCI is greater with a lighter vehicle.

Pavement condition also influences driver behavior such as route selection. In a study [18], a 21 km road in Indonesia was used to determine the relationship between pavement condition and vehicle speed and emissions. The PCI of the pavement surface was determined via visual inspection. The data collected included road dimensions, distress, and severity. Vehicle speeds were measured on different road segments and emissions were estimated. It was reported that vehicle speed decreased by 55% as the surface condition deteriorates from excellent to very poor, and emissions increased by 2.49%.

3. Methodology

The objective is to investigate the relationship between road pavement condition and vehicle speed, vibration, and in-vehicle noise. There are two test phases. In the first phase, PCI values are assigned to the road sections via

visual inspection. In the second phase, the BotlnckDectr app [6] is used to measure vehicle parameters. These results are analyzed to develop relationships between road pavement condition and vehicle speed, vibration, and in-vehicle noise.

3.1. Phase 1

In the first phase, a 7 km two-lane section of the Grand Trunk Road highway was selected from the Chamkani Bus Rapid Transit (BRT) station to Pabbi in Peshawar, Pakistan. The GPS coordinates for this route are 3767426, 743824, and 750679, 3767299. Each lane of the route was divided into 50 m segments to obtain results as per ASTM-D6433-11 guidelines. A visual survey was carried out and the distress in each segment was determined. The date and time of the survey, road segment location, distress and severity, and the number of each distress type were recorded. The length of each distress, such as longitudinal wheel path cracks, joint cracks, and meandering cracks, was also measured as well as distress areas such as alligator cracks and raveling. The number of potholes and transverse cracks was also noted. Some examples are given in Figure 2.

Figure 2. Road surface distress observed (a) pothole, (b) alligator cracks, (c) rutting, (d) longitudinal cracks, (e) raveling and weathering, and (f) transverse cracks.

The severity of each distress was assigned based on the crack width as low, medium, or high. The percentage of each distress was calculated based on its occurrence. The PCI was then assigned based on this percentage density and the severity. A flowchart of the steps is given in Figure 3. For the 280 road segments, the number of good, satisfactory, fair, poor, and very poor segments was 51, 52, 81, 48, and 42, respectively. The remaining 6 segments had failed condition. As this number is much smaller than the other values, it is not used in the analysis.

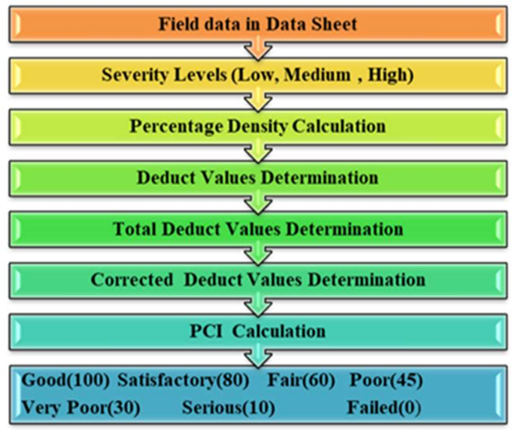

Figure 3. Flowchart for PCA calculations [5].

3.2. Phase 2

In the second phase, an automatic 1800CC Toyota Corolla Grande 2018 was driven over the road section. The vehicle width, length, and height are 1.775 m, 4.62 m, and 1.475 m, respectively. The tire size is 16 in with 35 PSI air pressure. To limit environmental and vehicle interference the trips were made between 12 AM and 2 AM (because of nearly non-existent on-road traffic) on March 8 to 30, 2020. Each lane was traversed 16 times, four times at 35, 45, 55, and 65 km/h. These speeds were chosen because this is the normal traffic flow speed on the selected road section. To quantify the impact of road pavement condition on vehicle free-flow speed, an additional 10 trips were undertaken with 5 trips on each lane. Vehicle speed, RPM, vibration, in-vehicle noise, GPS location, and time were recorded using an On-Board Diagnostic-II (OBD-II) ELM-327 scanner as shown in Figure 4.

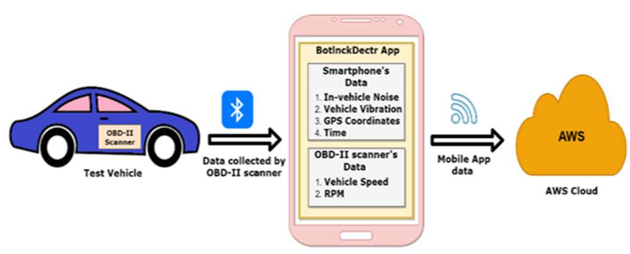

Figure 4. Block diagram of the experimental setup.

The smartphone app BotlnckDectr [19] was employed with Bluetooth on a Samsung Note 6 smartphone. The aforementioned app was developed by authors and explained in detail in a paper [19]. The in-vehicle noise was recorded using a KERN-SOHN SU 130 noise meter which has a range of 35 to 120 dB (the 35 dB threshold is in place to cancel out minor environmental noises). The smartphone and noise meter were placed on the dashboard of the test vehicle during test drives. Although other cloud platforms such as ThingSpeak are available, Amazon Web Services (AWS) was chosen because of its data upload frequency of 1 s as compared to 15 s for ThingSpeak [6, 20, 21].

4. Experimental results and analysis

In this section, the measured data are used to determine the impact of road pavement condition on vehicle speed, vibration, and in-vehicle noise.

4.1. Impact of pavement condition on vehicle speed

Previous results indicate that road pavement condition affects vehicular free-flow speed. To quantify this, 10 test drives were taken with 5 on each lane. Figure 5 shows that the average free flow speed is 74, 72.5, 70.3, 68.9, and 67.5 km/hr on the good, satisfactory, poor, and very poor road segments, respectively. This indicates that the average free-flow speed decreases from 74 to 72.5 km/h when the PCI decreases from 100 to 80.

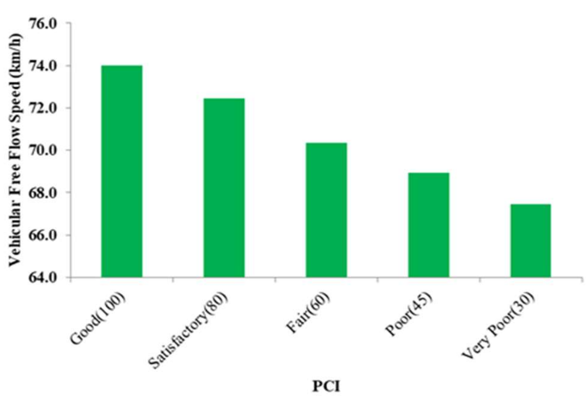

Figure 5. Vehicle free flow speed for different PCI levels.

From these results, the relationship between vehicle free flow speed and PCI can be expressed as follows:

$$y= -1.659x + 75.62 \tag{1}$$

where R^2 = 0.995 is the correlation coefficient. This coefficient indicates how well the data fit the models and has a value between 0 and 1. A value close to 1 indicates a good fit. The percentage decrease in vehicle free flow speed (FFS) versus the change in PCI is given in Figure 6. This shows that the free-flow speed decreases by 2% when the pavement surface condition changes from good to satisfactory. The decrease in free flow speed is 4.9%, 6.8%, and 8.8% when the PCI changes from good to fair, good to poor, and good to very poor, respectively.

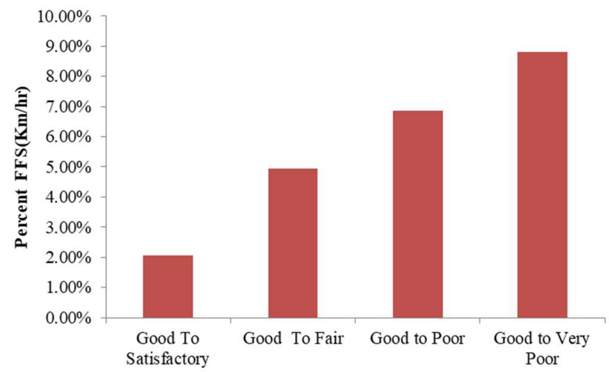

Figure 6. Percentage decrease in free flow speed versus the change in pavement surface condition.

4.2. Impact of pavement surface condition on in-vehicle noise

In-vehicle noise is a combination of noise generated from tire-pavement interaction and engine, vibration and ambient sources (such as on-road traffic). Vehicle speed contributes the most to in-vehicle noise levels. Figure 7 shows that the average in-vehicle noise is 78.1, 78.8, 79.2, and 80.1 dB at 35, 45, 55, and 65 km/h respectively. With the other parameters constant, there is an approximate difference of 2 dB between 35 km/h and 65 km/h.

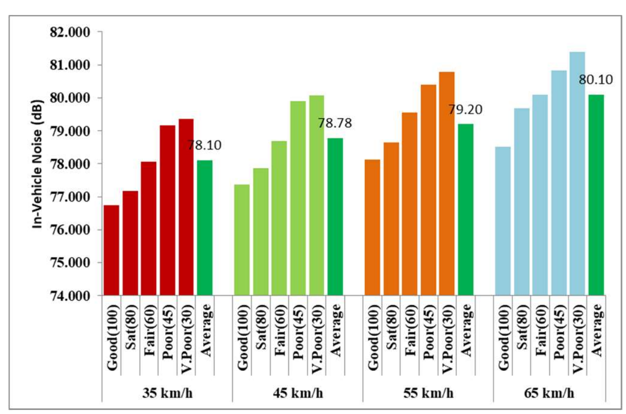

Figure 7. In-vehicle noise versus speed for different PCI levels.

Road pavement condition is an important factor contributing to in-vehicle noise. Figure 7 shows the in-vehicle noise level versus speed for different PCI levels. This shows that the noise level at 35 km/h is 76.5 dB and 79.2 dB for good and very poor road pavement conditions, respectively, which is an increase of 2.7 dB. The results are similar for speeds of 45 km/h, 55 km/h, and 65 km/h. For a given speed, the percentage change in in-vehicle noise from good to satisfactory, good to fair, good to poor, and good to very poor road conditions are given in Figure 8. This shows that when the vehicle speed is 35 km/h, the corresponding in-vehicle noise level is increased by 0.5%, 1.7%, 3.1%, and 3.3%, respectively. The increases are similar for other speeds. For example, at 65 km/h, the in-vehicle noise increased by 3.3% when the road pavement condition changed from good to very poor.

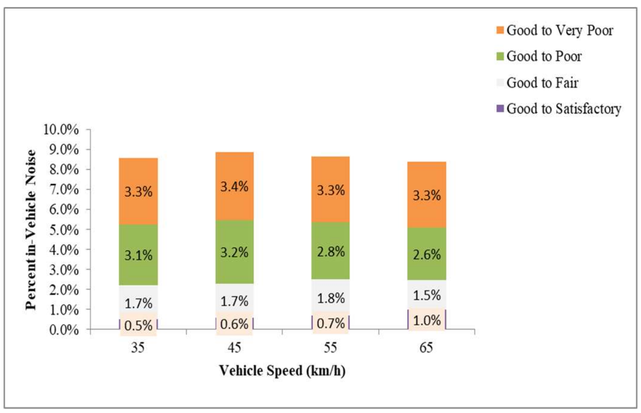

Figure 8. Percentage change in in-vehicle noise versus vehicle speed for different PCI levels.

Figure 9 presents the relationship between in-vehicle noise and PCI. This shows that the relationship is approximately linear which gives the following expressions:

35 km/h: $y = -0.0574x + 80.94$ (2)
$R^2 = 0.96$

45 km/h: $y = -0.0586x + 81.51$ (3)
$R^2 = 0.96$

55 km/h: $y = -0.0522x + 82.38$ (4)
$R^2 = 0.986$

65 km/h: $y = -0.0587x + 82.84$ (5)
$R^2 = 0.98$

where R^2 is the correlation coefficient. The correlation coefficient is above 0.95 in all cases which indicates an excellent fit to the data.

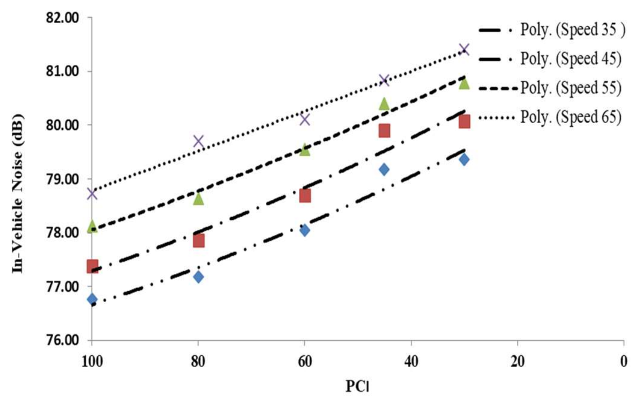

Figure 9. In-vehicle noise versus PCI at speeds of 35, 45, 55, and 65 km/h.

4.3. Impact of pavement conditions on vehicle vibration

Vehicle vibrations are generated mainly through road-tire interaction and are a major source of passenger discomfort and fatigue. The average vehicle vibration amplitude at speeds of 35, 45, 55, and 65 km/h is given in Figure 10 for different pavement conditions. This shows that the vibration amplitude is 2.76, 2.94, 3.18, 3.14, and 3.58 m/s^2 at 35 km/h for good, satisfactory, fair, poor, and very poor surface conditions, respectively. At this speed, an increase of 0.82 m/s^2 was observed when the pavement condition changed from good to very poor.

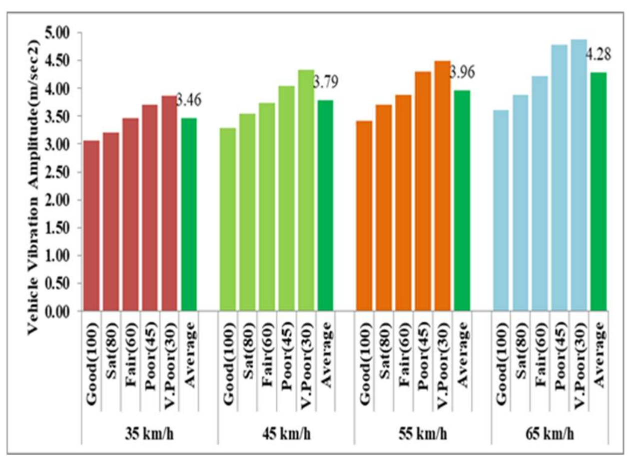

Figure 10. Vehicle vibration versus speed and PCI level.

Vehicle speed has a significant influence on vibration levels. For example, the average vibration amplitudes at 45 km/h are 3.29, 3.54, 3.74, 4.04, and 4.33 m/s^2 while at 55 km/h they increase to 3.4, 3.70, 3.88, 4.30, and 4.50 m/s^2 on good, satisfactory, poor, and very poor roads, respectively. Thus, it can be concluded that vehicle speed and road pavement condition are major contributors to vehicle vibration.

The effect of road surface condition on vehicle vibration is given in Figure 11. This shows that the increase in vibration at a given vehicle speed as the PCI varies from good to satisfactory, good to fair, good to poor, and good to very poor. At 35 km/h, the vibrations increase by 7%, 15%, 24%, and 30% when the PCI varies from good to satisfactory, fair, poor, and very poor, respectively. A similar increase in vibration was observed at speeds of 45, 55, and 65 km/h.

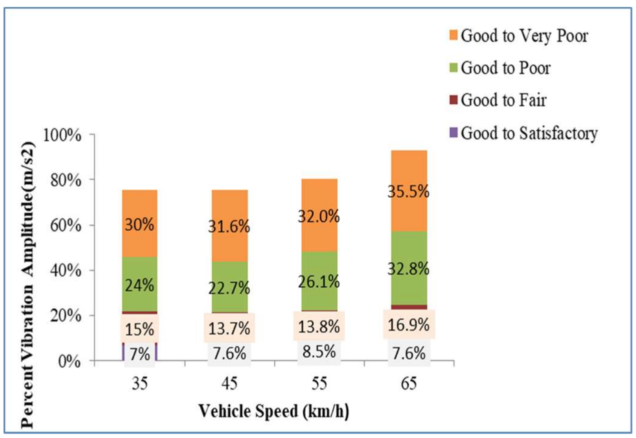

Figure 11. Percent increase in vehicle vibration with PCI versus vehicle speed.

The relationship between PCI and vehicle vibration at different speeds is shown in Figure 12. These results indicate a linear relationship which is given by the following expressions:

35 km/h: y=-0.0169x+4.07 (6)
R^2 = 0.9967

45 km/h: y=-0.0265x+5.04 (7)
R^2 = 0.9956

55 km/h: y=-0.0251x+5.21 (8)
R^2 = 0.9817

65 km/h: y=-0.0251x+5.21 (9)
R^2 = 0.9817

The correlation coefficients are above 0.98 which indicates an excellent fit to the data. That is, the correlation coefficient is close to 1. Thus, vehicle vibration increases linearly as the PCI changes from good to very poor.

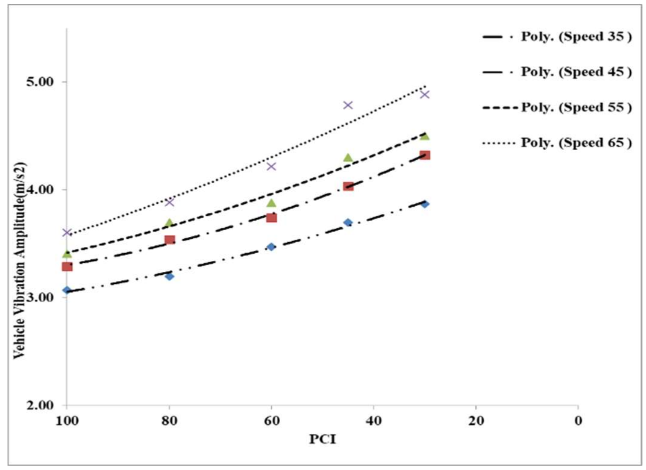

Figure 12. Vehicle vibration versus PCI at speeds of 35, 45, 55, and 65 km/h.

5. Conclusion

In this work, the relationship between road pavement conditions and vehicle speed, vibration, and in-vehicle noise was investigated. A 7 km two-lane highway in Peshawar, Pakistan, was examined using ASTM D6433-11 guidelines to assign PCI values. For the 280 road segments, the number that was good, satisfactory, fair, poor, and very poor was 51, 52, 81, 48, and 42, respectively. To measure vehicle vibration and in-vehicle noise, a smartphone app BotlnckDectr was used to measure vehicle speed, RPM, in-vehicle noise, vibration, GPS location, and time. The parameters were transmitted to the AWS cloud using a smartphone. The tests were conducted using a 2018 1800CC Toyota Grande, 16 on each lane of a two-lane highway at constant speeds of 35, 45, 55, and 65 km/h. Ten additional tests were done to determine the impact of pavement surface conditions on vehicle free-flow speed. The data obtained were analyzed to obtain the relationships between pavement surface condition and in-vehicle noise, vibration, and free-flow speed.

This research paper provides valuable insights into the linear relationship between PCI and a vehicle's speed, vibration, and in-vehicle noise. However, there is still a

lot of scope for further research in this area. In future research, the study can be expanded to include more parameters such as vehicle type (make, model, engine size, tires) and driver's vital signs (heart rate, blood pressure) to obtain a more comprehensive understanding of the impact of PCI on driving. Multiple vehicles can be used to collect data, and monitoring drivers' vital signs can help quantify the impact of pavement conditions on driver fatigue. This can lead to the development of better road maintenance strategies, improved driver safety and comfort, and sustainable transportation.

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